Considerations for and Examples of a Linear Collider Physics Program

May 10, 2001

Joel Butler

Fermilab

Goal of This Talk

- The Linear Colliders we are discussing are capable of producing a few hundred fb^{-1}/year
- We hear many comments about different running modes to study particular physics. I was asked to address the following issues:
  - **Are the various running modes compatible or do the various physics topics have conflicting requirements?**
  - **Do the luminosity books balance – that is, can the expected luminosity deliver the advertised physics, or is the luminosity inadequate or severely overbooked?**
- Other e^+e^- colliders, **albeit with different production characteristics for the physics of interest**, have suffered from problems because optimal running modes for various topics were in conflict and you were forced to chose which physics to emphasize – you couldn't do it "all at once" as you can with a hadron collider.

Outline

- What are we trying to accomplish with this class of machine?
- Possible machine operating modes
- What sets the context in which we can proceed to discuss these “operational” issues?
  - This will include a review of the key physics issues, but considered from the viewpoint of their requirements on the machine operating mode and demands on its luminosity
- Possible Physics knowledge “initial conditions” or “scenarios” and associated run plans
- Conclusions

What are we trying to achieve with this class of machines

- To elucidate the nature of Electroweak symmetry breaking
  - Issue is not just the discovery of a Higgs-like object
    - A standard model Higgs has serious issues associated with it. It receives radiative corrections from heavy objects which are quadratic in the mass and have to be removed by highly "delicate" fine tuning procedures
    - If the problem is "cured" by invoking new symmetries such as supersymmetry, then the symmetry is obviously broken, so we have to understand that. Ditto for any new "dynamics"

It is likely that some of the particles associated with this phenomenon will be seen before an LC is operating. The discovery of such particles may open up this area of experimental investigation of EWSB, but is not likely to close it out . The initial observations will raise new questions and may tell how best to proceed to answer them.

Bad Baseball Analogy

Baseball symmetry study

Contexts for Proceeding with the Discussion

- The machine
- Possible operating modes
- Our <u>current</u> physics understanding
- The **“then year”** physics Scenario

This exercise necessarily involves some crystal ball gazing. At best, we can identify broad classes of situations we could confront and ask whether the machine we can imagine has enough luminosity and operational flexibility to deal with them successfully

The machine context

(grossly simplified)

- Take a very simplified view of the "machine"
  - Energy in CM — 500-800-1000 GeV
  - Beam smearing — 3-4%
  - Luminosity — 2-3 X $10^{34}/cm^2$-s
  - e^- polarization — 80%

I am ignoring the issue of e^+ polarization. It seems to be viewed as "useful" but not crucial. There will also be other modes of running such as g-g, e^-e^-, or very low energy running. <u>For now, I assume these do not interfere with program I am going to describe.</u>

There will be (optimistically) 200-300 fb^{-1}/year (10^7 s) or 1000-1500 fb^{-1} over the first 5 years of operations.

Operating Modes - I

- **Sit** – for a particular topic, e.g. study of branching fractions of a Higgs at a known mass, sit at the center of mass energy that maximizes that physics – which means best tradeoff between signal, background, resolution…
- **Span** – sit at the highest energy obtainable. This obviously provides a broad look and produces physics over a wide range of topics – but is not necessarily “optimum” for any of them
- **Scan** – study a region where there is a threshold or transition of some kind by scanning the center of mass energy from just below to above the area of interest to see how things behave as they turn on

Operating Modes - II

- Polarization
  - Can enhance certain kinds of physics –especially asymmetries and interference effects
  - Can turn off or reduce certain kinds of background
  - Does polarization intended to enhance some physics hurt other physics you would like to do at the same time?

Electron Polarization

Comment: How this works at NLC, by way of SLC/SLD:

Bunch trains (120 Hz) are polarized at the source by a passing laser light through a Pockels cell –a nonlinear optics device based on applying a voltage across a crystal- which manipulates the index of refraction.

This light then falls on a Photocathode of GaAs, which emits polarized electrons. The individual bunch trains acquire ~80% polarization.

- **In "randomized polarization" running, the sign of the voltage on the Pockels cell is random (by train) so ½ the bunch trains have 80% RH polarization and ½ have 80% LH polarization. The voltage on the cell is provided to the experimenters for each bunch train so they can sort their data into (mostly) "RH" or "LH" samples for polarization studies or ignore the voltage and add everything up**
- **If you want to "emphasize" one polarization, you can fix the sign of the Pockels cell voltage and get 80% polarization for your preferred handedness– called "polarized" running.**

LBS Worksheet

CM Energy	Run Duration	e^- Polarization	Goal

I am more interested in what kind of conditions are best for various physics topics, how sensitive they are if you are not at their optimum, and how/whether various running conditions can coexist gracefully. A few detailed scenarios will be discussed, but only towards the end of the talk.

Current Physics Context - I

1. **There are many reasons to believe that wonderous, <u>unanticipated</u> new discoveries await us at higher energies**
2. **Having said that, I want to investigate how this machine could address the main issues of ElectroWeak Symmetry Breaking under various unfolding scenarios**
3. **But keep point 1 in mind by using whatever flexibility exists in addressing point 2 to retain the highest possible openness to new physics, <u>especially by providing lots of running at energies close to the top machine energy</u>**

Current Physics Context - II

- Higgs physics – Based on our current understanding, we expect that at least one Higgs-like object will have been found at the Tevatron or LHC before this machine turns on. However, the SM model Higgs has serious problems since its radiative corrections lead to quadratic divergences. This can be fixed by renormalization but if the next relevant scale is the Planck scale, it raises the “naturalness” issue and the “hierarchy problem” – why is the Higgs mass so low compared to the Planck scale?

Current Physics Context - III

- A natural cure is to have another family of particles at or near the EW scale which contributes to EWSB
  - SUSY is considered by many the premier candidate
  - But whatever appears it will be important to study it in detail to understand
    - Its relation to the Higgs sector
    - Since it is likely to associated with a new symmetry, which would be broken, or new dynamics, we would need to study that as thoroughly as possible, and understand how it works and what it implies, if anything, for higher energy behavior

I use SUSY in the following exercise because it is expected to have a rich spectroscopy within the reach of a 500 GeV Linear Collider, is very dependent on polarization and is therefore very demanding on machine operating conditions

Why Study the Higgs?

- Once you know the mass of the “Standard model Higgs”, everything else about it is fixed
- If you see a Higgs-like object and want to “prove” it is the SM Higgs and that it alone is really the object that provides mass to the gauge bosons and all other particles, you should verify that it has exactly the properties “prescribed” by SM
- If the observed Higgs is not truly the Standard Model Higgs, its couplings and decay properties should show deviation from the highly defined SM Higgs, e.g:

The branching fractions in the SM are completely determined once the Higgs mass is known. Departures signify a more complex Higgs sector and give clues about its nature

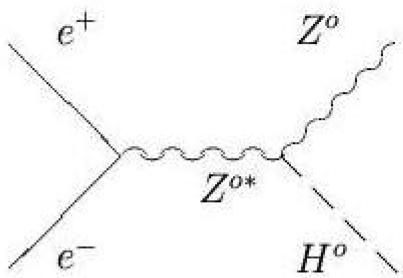
Everything You Always Wanted to Know about the Higgs –a.k.a the Higgs Profile

- Mass
- Width
- Spin
- Parity
- CP
- Coupling to gauge Bosons
- Coupling to fermions
    - Charge 1/3 quarks
    - Charge 2/3 quarks
    - Leptons
- Higgs self couplings
    - Triple coupling
    - Quartic coupling

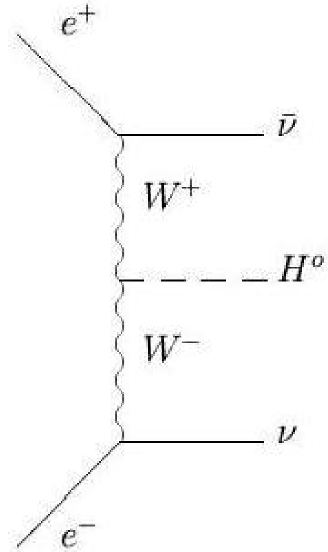
We'll go through this program seeing which pieces require **scans**, which **continuum running -span**, which **sitting at optimal energies**. The question is whether it is likely that the luminosity and other requirements can be met by our collider under all circumstances.

Higgs Physics for the Theory Challenged - I

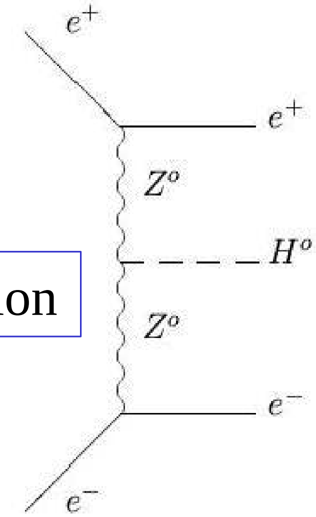
Production Mechanisms



Z Higgs-strahlung



W (Z) Fusion



$$\sigma(e^+e^- \to ZH) = \frac{g^2_{ZZH}}{4\pi}\frac{G_F(v_e^2+a_e^2)}{96\sqrt{2}s}\boxed{\beta_{HZ}}\frac{\beta^2_{HZ}+12M_Z^2/s}{(1-M_z^2/s)^2}$$

$$\beta^2_{ZH} = \left[1-(M_Z+M_H)^2/s\right]\left[1-(M_Z-M_H)^2/s\right]$$

$$\nu_e = -1+4\sin^2\theta_W;\; a_e = -1$$

$$\sigma(e^+e^- \to \bar{\nu}_e\nu_e H) = \frac{g^2_{WWH}}{4\pi}\frac{G_F^2}{8\pi^2}\left[(1+M_H^2/s)\log\frac{s}{M_H^2} - 2(1-M_H^2/s)\right]$$

(Z fusion is suppressed by NC/CC ratio and is lower by a factor of 10)

Asymptotic behavior→ 1/s Depends on g_{ZZH} Threshold behavior→β_{hz} Not very sensitive to polarization	Asymptotic behavior→ $\log\frac{s}{M_H^2}$ Depends on g_{WWH} Dominates at high CM energy Much reduced by RH polarization

HPTC - II

Total Width and Branching Fractions

Some tree level formulae:

$$\Gamma(H^o \to f\bar{f}) = \frac{N_c g^2 m_f^2}{32p\, M_W^2} b^3 M_{H^o}$$

$$b^2 = 1 - 4m_f^2 / m_{H^o}^2 \qquad N_c = 1\,(\text{leptons})\text{ or }3\,(\text{quarks})$$

$$\Gamma(H^o \to VV) = \frac{g^2 d}{128p} \frac{M_{H^o}^3}{M_V^2} \sqrt{1 - X_V}\,(1 - X_V + \frac{3}{4} X_V^2)$$

$$X_V = 4M_V^2 / M_{H^o}^2 \text{ and } d = 1 (V = Z), 2 (V = W)$$

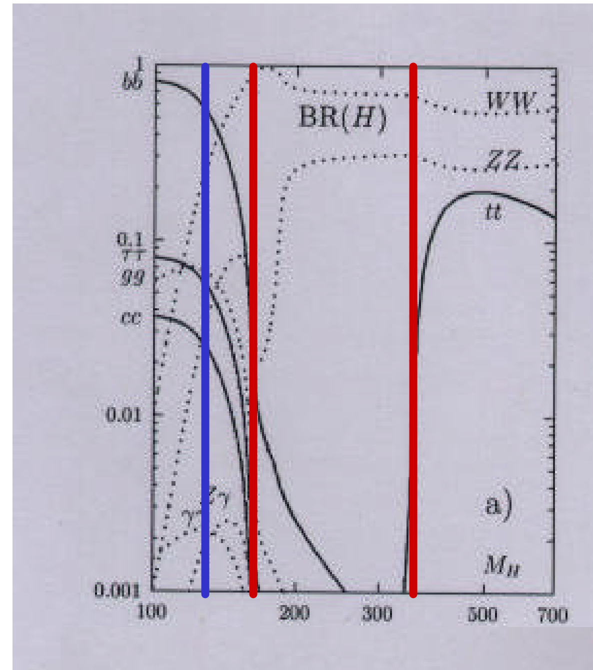
$$\Gamma(H^o \to W^* W) = \frac{3g^4 M_{H^o}}{512p^3} F(M_W / M_{H^o})$$

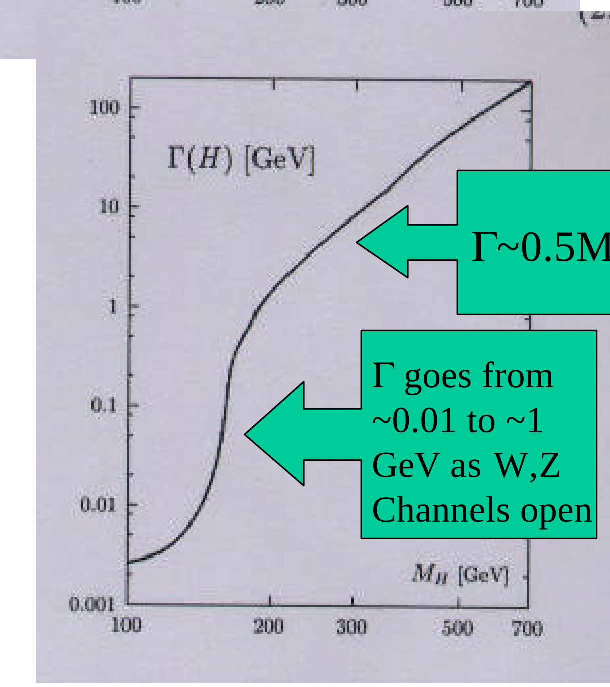
$$\Gamma(H^o \to Z^* Z) = \frac{g^4 M_{H^o}}{2048p^3} \frac{7 - \frac{40}{3}\sin^2 q_W + \frac{160}{9}\sin^4 q_W}{\cos^4 q_W} F(M_Z / M_{H^o})$$

where

$$\mathrm{F(x)} = -\left|1 - \mathrm{x}^2\right| \left(\frac{47}{2} x^2 - \frac{13}{2} + \frac{1}{x^2}\right)$$

$$-3(1 - 6x^2 + 4x^2)\left|\ln x\right| + 3\frac{1 - 8x^2 + 20x^4}{\sqrt{4x^2 - 1}} \cos^{-1}\left(\frac{3x^2 - 1}{2x^3}\right)$$





$\Gamma \sim 0.5 M_H^3$

Γ goes from ~0.01 to ~1 GeV as W,Z Channels open

HPTC - III

The Higgs partial widths are strong functions of both the Higgs mass and the decay product masses.

If the Higgs mass is well below $2M_W$, there are several decay modes involving fermions available, which have appreciable branching fractions and the total width is small– <u>too small to measure directly from mass reconstruction</u>

If the Higgs mass is over $2M_W$ but $<2M_t$, since the ratio, the only appreciable branching fractions are WW and ZZ, because

$$\frac{\Gamma_{f\bar{f}}}{\Gamma_{VV}} \sim \frac{N_c m_f^2}{M_H^2} <<< 1$$

Only the VV branching fractions and the total width can be measured directly

If $M_H > 2M_t$, it will be possible to measure the top branching fraction directly.

HPTC - IV

If you can’t measure a coupling directly, then you have other methods:

- g_{vvH} can be measured from cross sections
- g_{ttH} can be measured from the cross section for Higgstrahlung off a top pair, but this requires high energy and high luminosity
- g_{ttH} may be inferred from H→gluon-gluon which is dominated by the loops containing a top (model dependent!)

For M_H<200GeV, can get total width from a branching fraction measurement and a measurement of a the corresponding coupling constant by another means – i.e. from a cross section (Some of you may remember this from the J/ψ)

If the Higgs sector is more complicated – e.g. SUSY– there might be more Higgs particles. However, since they are responsible for particle masses, they are constrained to make up the equivalent SM coupling:

$$\sum_i g^2_{h_i^o VV} = g^2_{H_{SM}VV} \quad \text{e.g} \quad \begin{cases} g^2 = g_1^2 + g_2^2; \\ g_1, g_2 \text{ are the couplings of } h^o, H^o \end{cases}$$

$$\sum_i g_{h_i^o VV}\, g_{h_i^o f\bar{f}} = g_{H_{SM}VV}\, g_{H_{SM} f\bar{f}}$$

Departure from SM predictions→ new physics.
This sets a luminosity bar for the e^+e^- collider

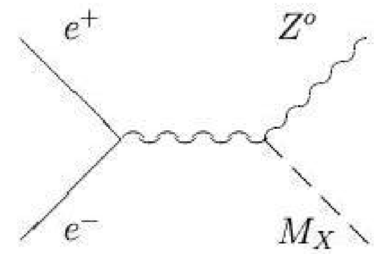
Higgs Physics for the Experimentally Challenged

Missing Mass Method for Isolating a Signal

In the process $e^+e^- \rightarrow Z+X$, a measurement of the Z momentum vector, allows one to compute the invariant mass of the the recoiling state "X", in this case mainly the Higgs:

Beam strahlung

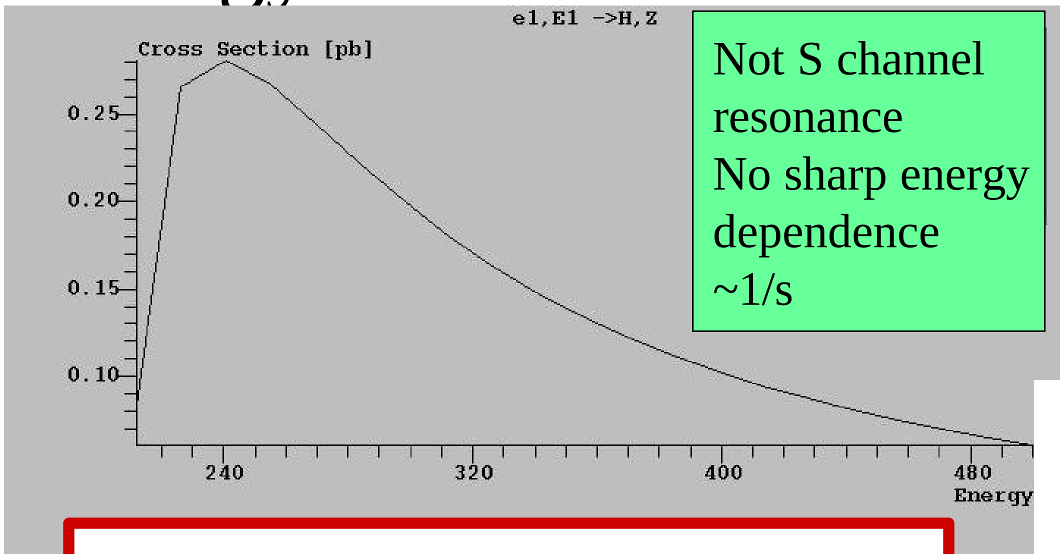
$$M_X = M_H = \sqrt{S - 2\sqrt{S}\, E_z + M_Z^2}$$



The Z signal can be most easily isolated and E_Z measured most accurately from $Z \rightarrow e^+e^-$ or $Z \rightarrow \mu^+\mu^-$. Can use jet-jet signal, also. The ability to see a mass bump recoiling against a measured Z, gives one a **model independent measurement** of the total number of Higgs' produced. Reconstruction of the individual decays then gives the actual absolute branching fractions (and any "invisible part").

Rates (ZH): 300 fb^{-1} X 250 fb = 75,000 Higgs produce
For $Z \rightarrow e^+e^-, \mu^+\mu^-$ (6.8%), we get 5100 events
Add $Z \rightarrow bb, cc, \tau\tau$ (30%) X0.5 (recon,background), we get 16,350 event

Energy Considerations



Not S channel resonance
No sharp energy dependence
~1/s

CM Energy	Cross Section (pb)	Rel Lum	Product
250	0.25	0.5	0.125
350	0.14	0.7	0.098
500	0.06	1.0	0.06

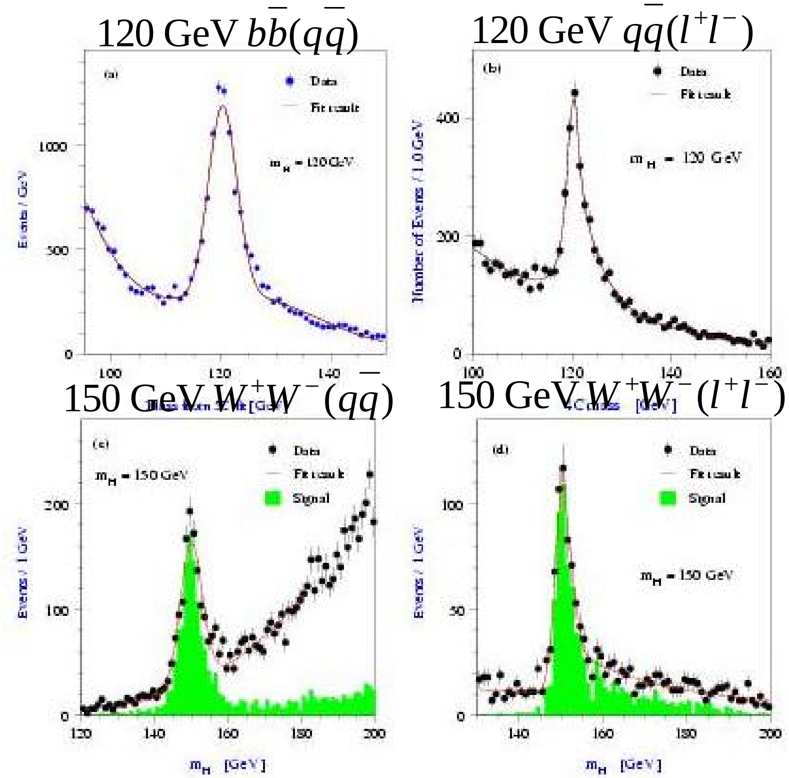


Figure 2.2.1: *The Higgs boson mass peak reconstructed in different channels with constrained fits for two values of M_H. (a): $H^0Z \to b\bar{b}q\bar{q}$ at $M_H = 120$ GeV; (b): $H^0Z \to q\bar{q}\ell^+\ell^-$ at $M_H = 120$ GeV; (c): $H^0Z \to W^+W^-q\bar{q}$ at $M_H = 150$ GeV; (d): $H^0Z \to W^+W^-\ell^+\ell^-$ at $M_H = 150$ GeV. The figures are for an integrated luminosity of 500 fb^{-1} at $\sqrt{s} = 350$ GeV.*

You gain about a factor of two by sitting at the peak of the cross section rather than at 500 GeV

Sit (weak)

250 GeV virtues:

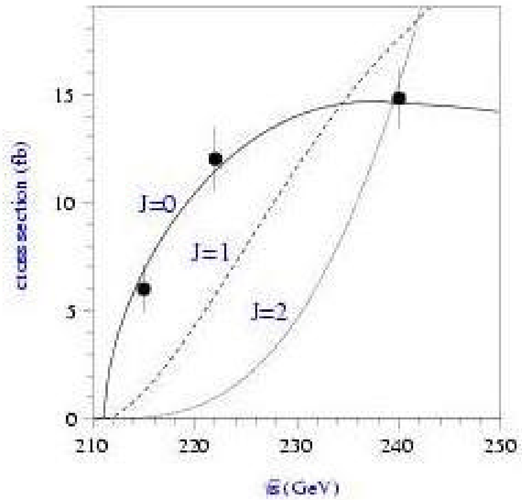
- highest rate
- Lowest background – no higher energy processes
- Lower beamstrahlung and better resolution on Z energy

500 GeV virtues:

- Can get other physics e.g. SUSY
- Z and Higgs in separate hemispheres

Spin and CP

Scan



The spin of the "Higgs candidate" can be determined by the behavior of the ZH cross section near threshold. Each point of the scan is 20 fb^{-1}. The Higgs mass is taken to be 120 GeV/c^2

BUT

It can also be determined by the Z angular distribution in the continuum :

The CP even or odd nature of the Higgs candidate can be determined by measuring the angular distribution of the Z with respect to the beam direction in the lab

or Span

$$\frac{ds}{d\cos q_Z} = b_{HZ}\left[1+\frac{sb_{HZ}^2}{8M_Z^2}\sin^2 q_Z + h\frac{2sb_{HZ}}{M_Z^2}k\cos q_Z + h^2\frac{s^2b_{HZ}^2}{8M_Z^4}(1+\cos^2 q_Z)\right]$$

where $k = \dfrac{v_e a_e}{(v_e^2 + a_e^2)}$

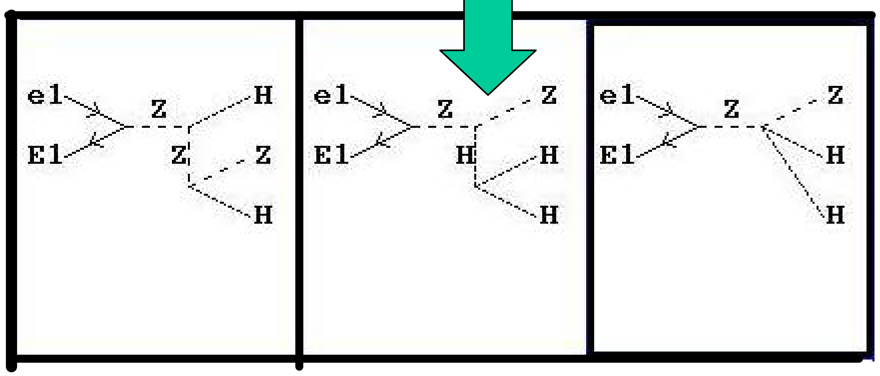
A $\sin^2\theta_Z$ behavior implies CP even, a $(1+\cos^2\theta_Z)$ CP odd, and a $\cos\theta_Z$ term mixed CP, i.e. CP violation

Multi-Higgs Coupling

$$V = l v^2 H^2 + l v H^3 + \frac{1}{4} l H^4$$

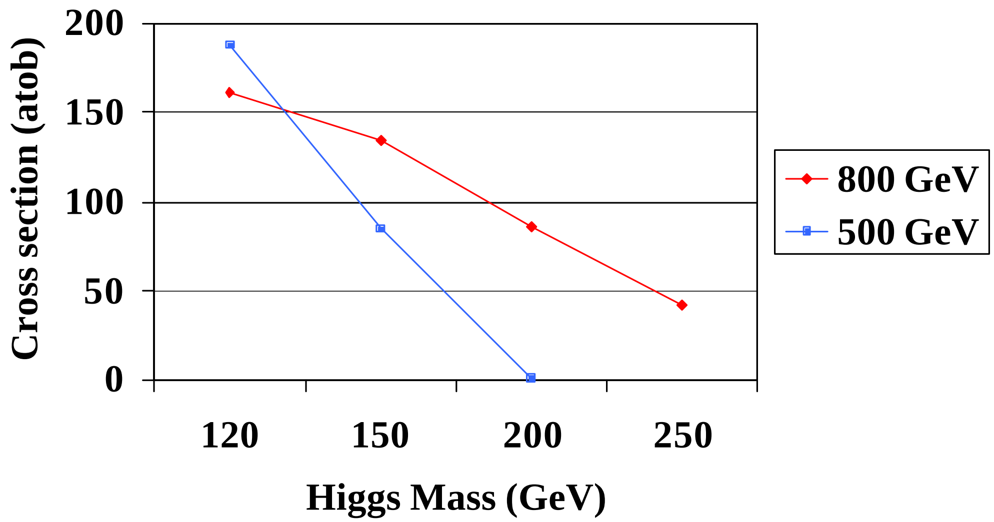
$1/2 M_H^2$

Span



Double Higgs production

Cross sections are small: ~10's to 100's atobarns. This gives dl/l of ~ 20% accuracy in about 5 years



There is not enough Luminosity to measure Quadrilinear coupling!!

SHPTC – V

Minimal SUSY has two complex scalar fields, which give mass to the Z^o, W^+, and W^- and have 5 fields left over to form new Higgs's: **h^o (CP even), H^o(CP even), A^o(CP odd), H^+, and H^-.** There are two vacuum expectation values and **tan b = v_1/v_2**. The two neutral Higgs mix to form the h^o and H^o and the mixing angle is called a. Only one of the masses are one angle are independent.

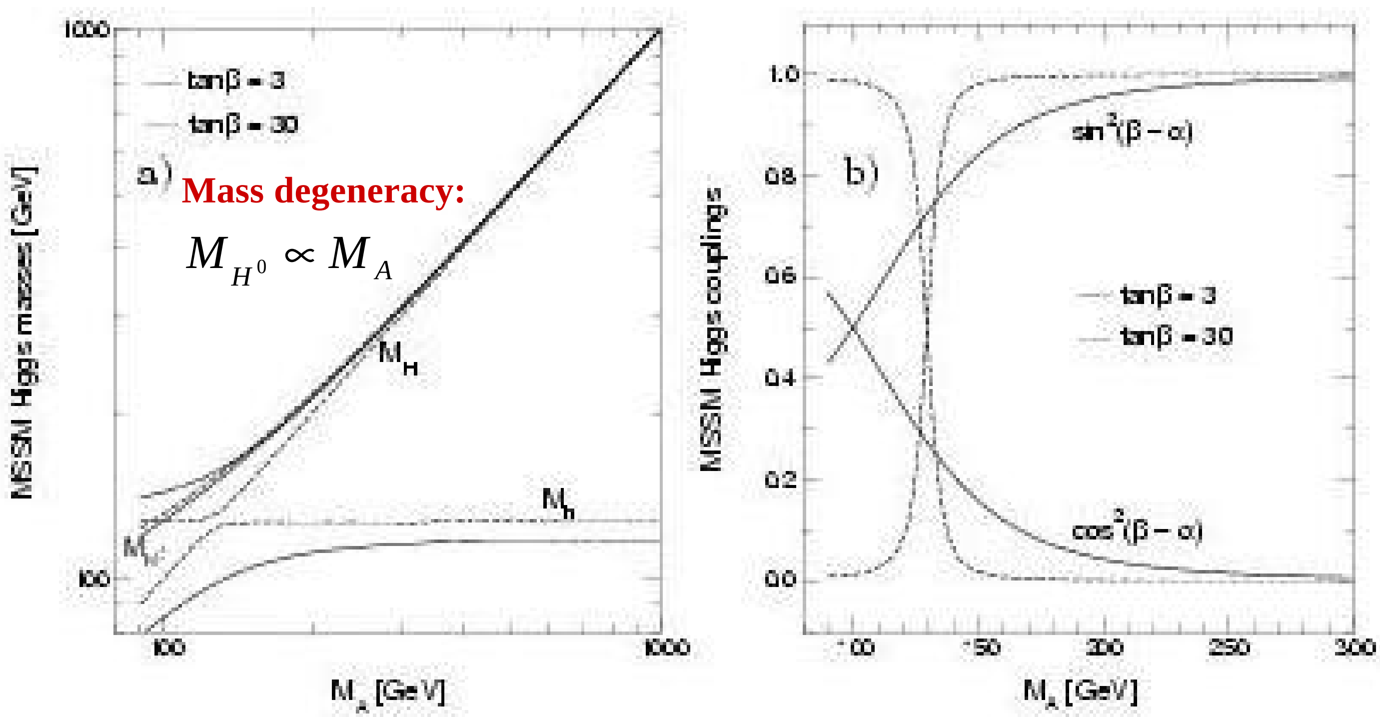


Figure 2.1.6: *The masses of the Higgs bosons in the MSSM (a) and their squared couplings to the gauge bosons (b) for two representative values of* $\tan\beta = 3$ *and* 30 [29].

Decay Modes and Branching Ratios

Decay Modes of SUSY Higgs:

h^o : As in SM

H^o: can go to same modes as h^o and $h^o h^o$ if mass is > 250 GeV

A^o: is not allowed to go to ZZ or WW. Will go by bb $\tau\tau$, Zh, or tt depending on M_A.

H^+: $\tau\nu_\tau$ or, if heavy tb

[Decoupling Limit]: if b is near 90^o (large tan b) and a is near 0^o, then only h^o has significant couplings and SUSY looks like SM. This occurs if M_A is large.

β,α dependence of decay modes:

$q_{2/3}$ is any charge 2/3 quark

$q_{1/3}$ is any charge 1/3 quark

$$H^o q_{2/3}\bar{q}_{2/3} : \frac{\sin a}{\sin b} \quad H^o q_{1/3}\bar{q}_{1/3} : \frac{\cos a}{\cos b}$$

$$h^o q_{2/3}\bar{q}_{2/3} : \frac{\cos a}{\sin b} \quad h^o q_{1/3}\bar{q}_{1/3} : \frac{-\sin a}{\cos b}$$

$$A^o q_{2/3}\bar{q}_{2/3} : \cot b \quad A^o q_{1/3}\bar{q}_{1/3} : \tan b$$

Higgs-gauge bosons couplings relative to SM Higgs

f^o refers to the SM Higgs

$$\frac{g_{h^o VV}}{g_{f^o VV}} = \sin(b - a)$$

$$\frac{g_{H^o VV}}{g_{f^o VV}} = \cos(b - a)$$

SUSY Higgs Cross Sections

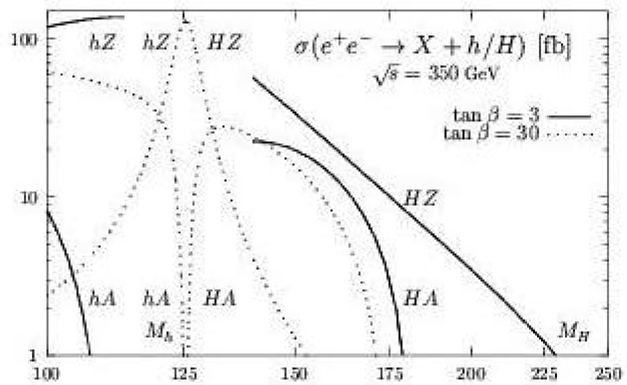


Figure 2.1.7: *Production cross sections of the MSSM neutral Higgs bosons at* $\sqrt{s}$ = 350 *GeV in the Higgs-strahlung and pair production processes:* $\tan\beta = 3$ *and 30.*

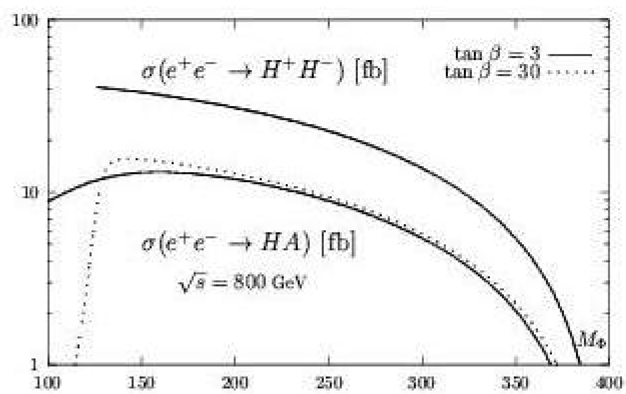


Figure 2.1.8: *Production cross sections for the associated* H^0A^0 *and the* H^+H^- *production mechanisms at* $\sqrt{s}$ = 800 *GeV as functions of the A and* $H^\pm$ *masses, respectively, for* $\tan\beta = 3$ *and 30.*

$$e^+e^- \to ZH^o$$

$$e^+e^- \to H^0A^0, (h^0A^0)$$

Span

$$e^+e^- \text{ can't produce } ZA^0$$

A^o does not couple to VV

Typical cross sections are order 100-10 fb^{-1} for H^o and order of 1-20 fb^{-1} for A^o at 350 GeV

Typical cross sections for the H^+ are 10-100 fb^{-1} and for A^o are around 10 fb^{-1} at 800 GeV

There will be enough luminosity to have a shot at these if masses are below 300 GeV.

E_{cm} of 800-1000 GeV definitely extends the reach

Heavier (single) Higgs

For M_H> 200 GeV/c^2, it decays almost 100% into WW and ZZ until 350 GeV/c^2 where $t\bar{t}$ is permitted.

You can still measure M_H, Γ, and the quantum numbers.

The main branching ratios are ZZ and WW.For SM Higgs:

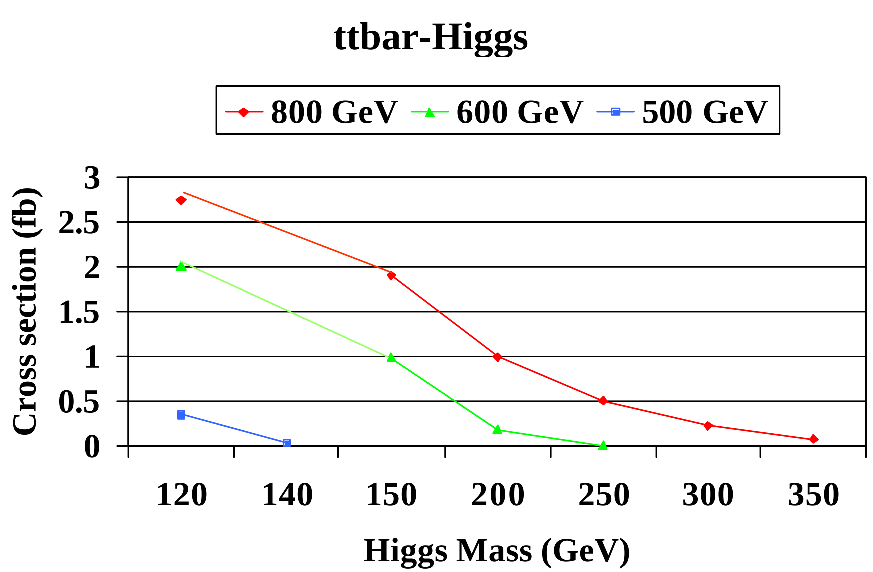
$$\frac{\Gamma(H \to ZZ)}{\Gamma(H \to WW)} = \frac{64}{128}\frac{\sqrt{1-X_Z}}{\sqrt{1-X_W}}\frac{1-X_Z+3/4X_Z^2}{1-X_W+3/4X_W^2}; X_Z = \frac{4M_Z^2}{M_H^2}; X_W = \frac{4M_W^2}{M_H^2}$$

Polarization of vector mesons: $\frac{\Gamma(H \to V_T V_T)}{\Gamma(H \to V_L V_L)} = \frac{1/2X_V^2}{1-1/2X_V^2}$

Trilinear coupling: more significant in this scenario?

Probably span

span

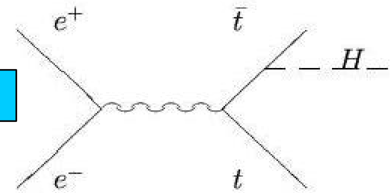


Top coupling: if M_H>350 GeV, the branching fraction to top is 10-20% and the cross section for a 350 GeV Higgs

σ(ZH)= 1.3,1.5,1.2 fb at 500,600 800 GeV

σ(W$\nu\nu$)= 3.9,12.5,40 fb at 500,600,800

If M_H~200 GeV, use t-tbar-Higgs:



A 0th Order SUSY Primer-I

Recall that in SUSY, for sparticles "L" and "R" refer to having the same quantum numbers, e.g. weak isopsin and hypercharge, (except for spin) as the normal "lefthanded electrons" and "righthanded electrons", respectively. All couplings are the same as for normal particles e.g. only "LH" sparticles couple to W's.

R-Parity: $P_R = (-1)^{3(B-L)+2S}$

A multiplicatively conserved quantum number, which is 1 for particles and –1 for sparticles. This is not a requirement of SUSY but, if imposed, provides an easy way to avoid various problems. If conserved there is the lightest SUSY particle, the "LSP", is stable.

SUSY makes contact with every "benchmark" physics process: CP violation, flavor violation, baryon and lepton number violation.

A 0th Order SUSY Primer-II

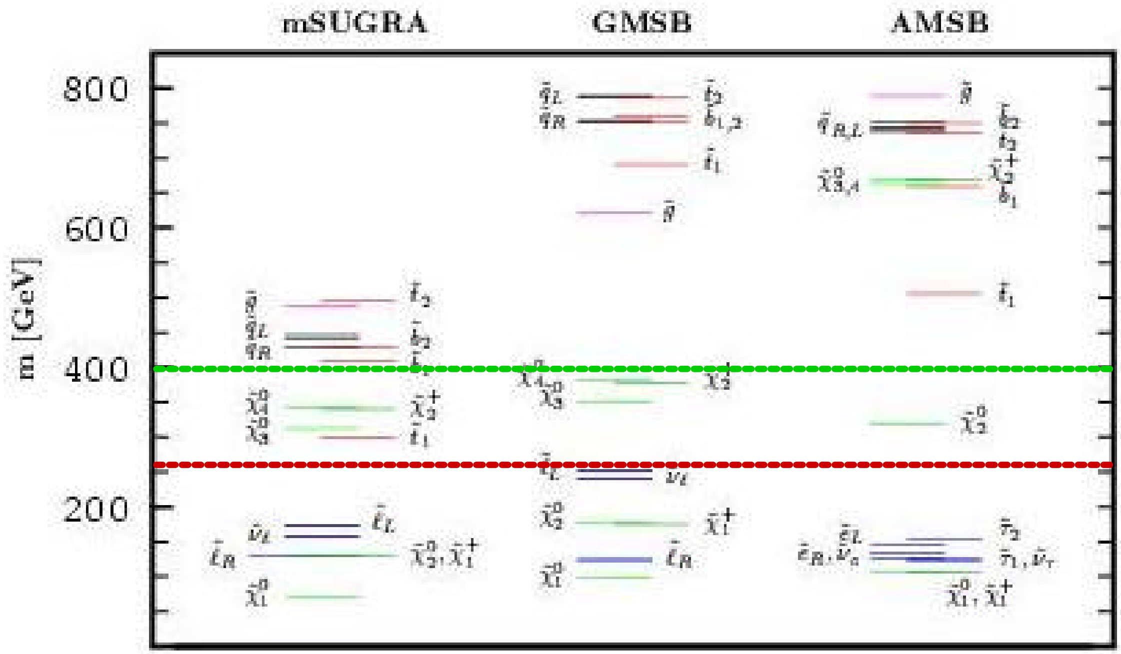


Figure 3.0.1: *Examples of mass spectra in mSUGRA, GMSB and AMSB models for* $\tan\beta = 3$, *sign* $\mu > 0$. *The other parameters are* $m_0 = 100$ *GeV*, $m_{1/2} = 200$ *GeV for mSUGRA;* $M_{mess} = 100$ *TeV*, $N_{mess} = 1$, $\Lambda = 70$ *TeV for GMSB; and* $m_0 = 200$ *GeV*, $m_{3/2} = 35$ *TeV for AMSB.*

All these models have a neutralino, chargino, and at least one slepton below 250 GeV. Only mSUGRA has a squark (stop) below 400 GeV.

Is a SUSY program “compatible” or in conflict with the Higgs program?

The SUSY Spectrum depends in detail on SUSY breaking models and their many associated parameters. The lightest SUSY partilce is expected to be the “neutralino” – An admixture of the superpartners of the gauge bosons.
in many models, several superparticles have masses below a few hundred GeV and could be detected and studied by the machines we are discussing. **The mass spectrum is the key to pinning down SUSY breaking parameters**

SUSY Branching fractions

Illustrative only.Varies wildly with model/mass spectrum.

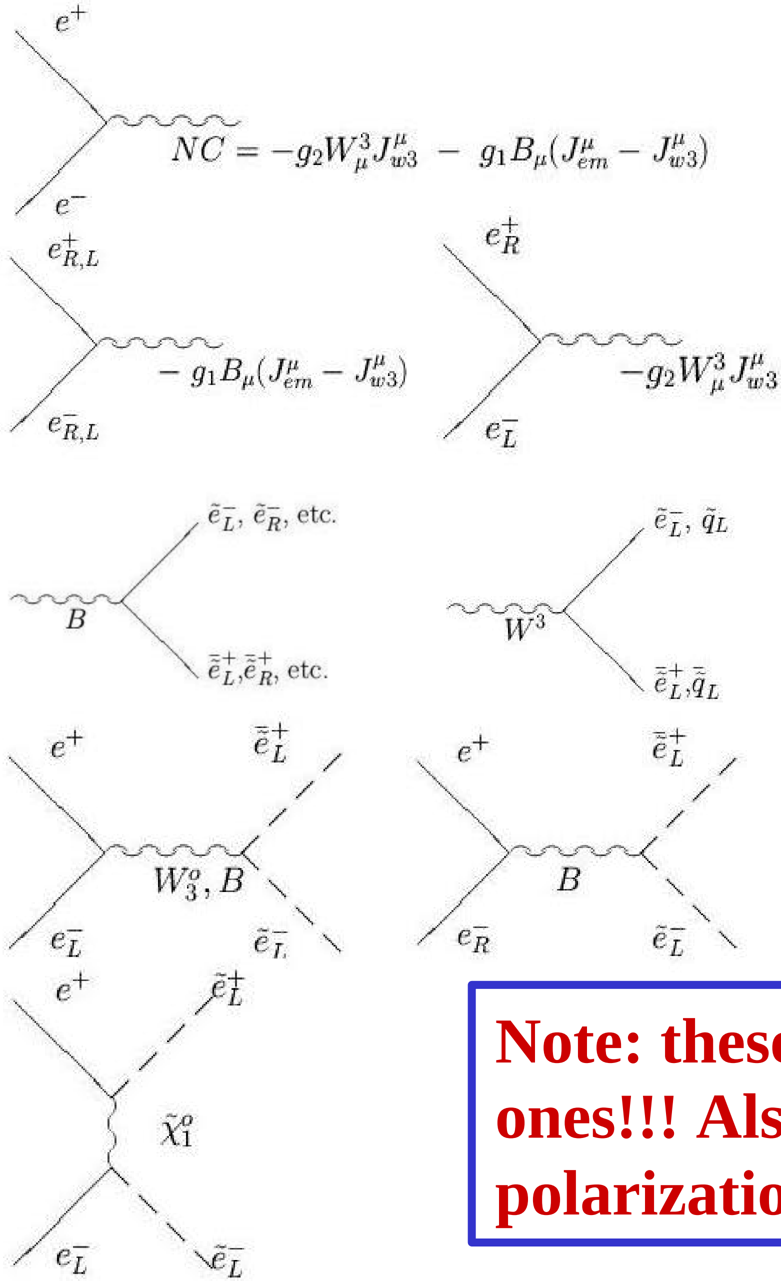
*→quasi two-body decay

Decay Mode	Fraction
$\tilde{c}^0_2 \to \tilde{c}^0_1 l^+ l^-$	49.7%
$\to \tilde{c}^0_1 q\bar{q}$	42.4
$\to \tilde{c}^0_1 n\bar{n}$	7.8
$\tilde{c}^0_3 \to \tilde{c}^\pm_1 W^\mp$	58.6
$\to \tilde{c}^0_1 Z^0$	22.2
$\to \tilde{c}^0_1 h^0$	10.1
$\tilde{c}^+_1 \to \tilde{c}^0_1 q\bar{q}$	66.3
$\to \tilde{c}^0_1 l^+ n_l$	33.7

Decay Mode	Fraction
$\tilde{n} \to \tilde{c}^+_1 e^-$	61.5% *
$\to \tilde{c}^0_2 n_e$	31.9
$\to \tilde{c}^0_1 n_e$	6.6
$\tilde{e}^+_R \to \tilde{c}^0_1 e^+$	99.0 *
$\tilde{e}^+_L \to \tilde{c}^+_1 \bar{n}_e$	54.4
$\to \tilde{c}^0_2 e^+$	24.2 *
$\to \tilde{c}^0_1 e^+$	21.4 *
$\tilde{t}_1 \to \tilde{c}^+_1 b$	64.6 *
$\to \tilde{c}^0_1 t$	35.4 *
$\tilde{b}_L \to \tilde{c}^0_2 b$	86.2 *
$\to \tilde{c}^-_1 t$	13.7 *

Smuons work the same as selectrons

SUSY Cross Sections are Polarization Dependent



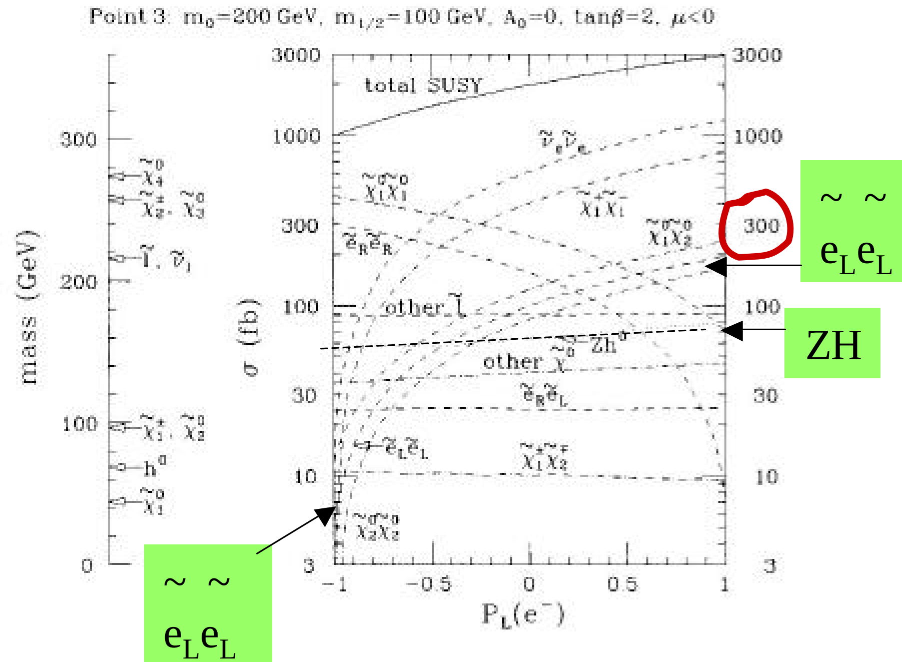
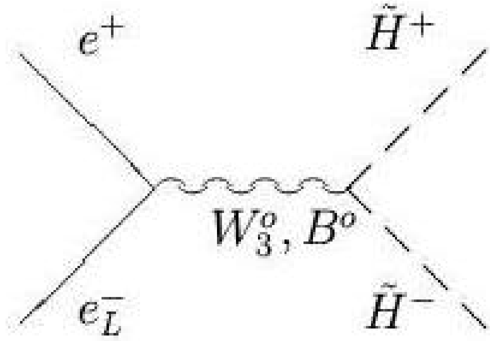
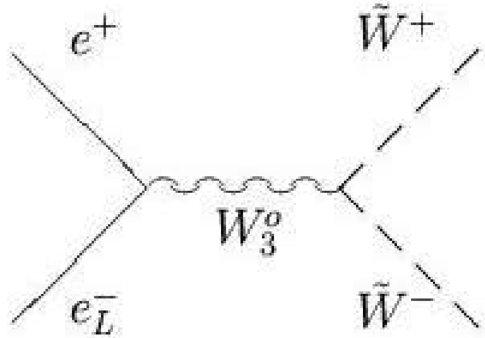


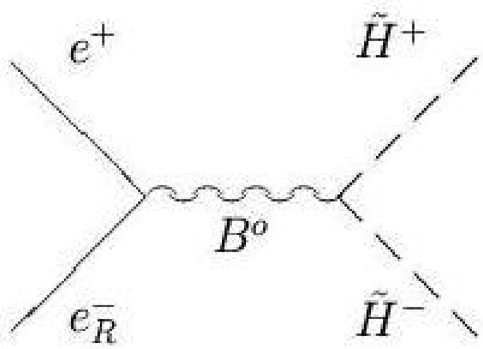
Figure 9: Cross sections of SUSY processes as a function of electron polarization for $\sqrt{s} = 500$ GeV, where $P_L(e^-) = 1.0$ corresponds to 100% left-handed polarization [3, 10].

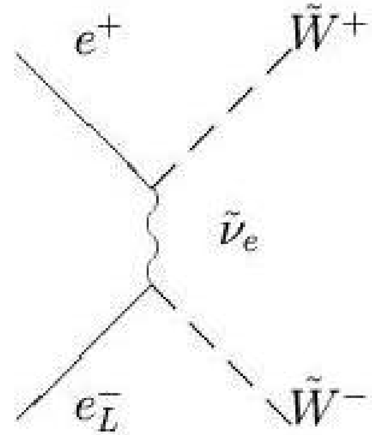
Note: these are DRAMATIC effects, not subtle ones!!! Also, ZH is only slightly effected by polarization. RH polarization kills W-fusion!!!!

Typical Polarization Studies

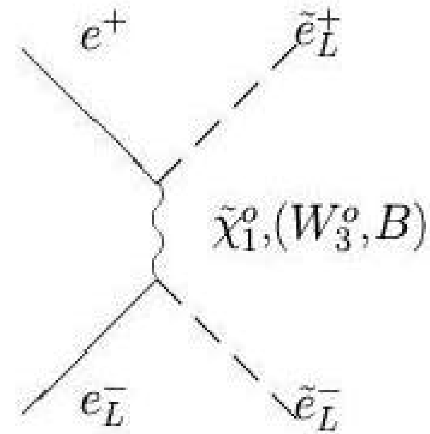


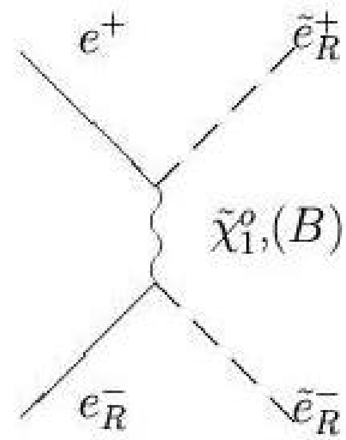






Study of gaugino
Or Higgsino
Character of
Charginos





Study of gaugino,
Higgsino content of
Neutralino (mixed)

SUSY Mass Measurement

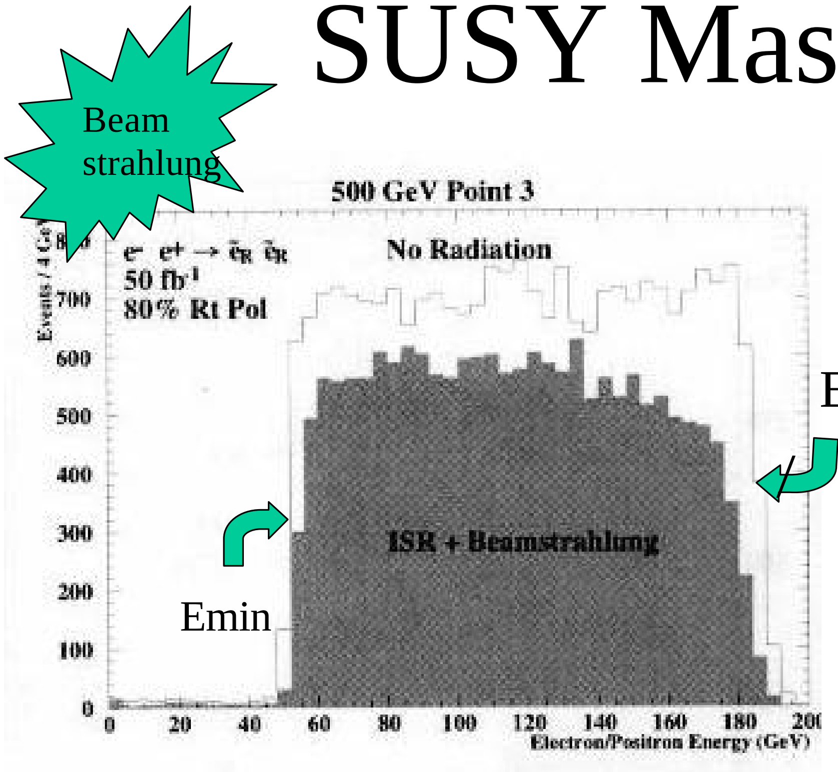
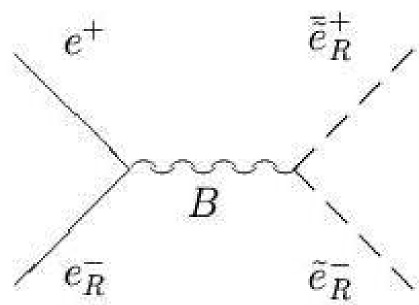


Figure 3: Effect of initial state radiation and beamstrahlung o the electron energy from $\tilde{e}_R^{\pm}$ decays.



$$\tilde{e}_R^+ \to \tilde{\chi}_1^0 e^+$$

$$E_{e_R,MIN,MAX} = \gamma^*(E^*_{e_R} \pm \beta^* p^*)$$

$$\tilde{m}_{e_R} = \sqrt{S}\sqrt{\frac{E_{\max}E_{\min}}{(E_{\max}+E_{\min})^2}}$$

$$M^2_{\tilde{\chi}_1^0} = \tilde{m}_{e_R}^{\,2} + s\left(\frac{E_{\max}E_{\min}}{E_{\max}+E_{\min}}\right) X \left(\frac{1}{E_{\max}+E_{\min}} - \frac{2}{\sqrt{s}}\right)$$

Note: We can get the neutralino mass for "free" from the measurement of the electron energy!

For a three body decay like $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 q\bar{q}$, you can see that if you use a limited range of M_{qq}, you can sort of capture the same effect.

Polarization and Backgrounds

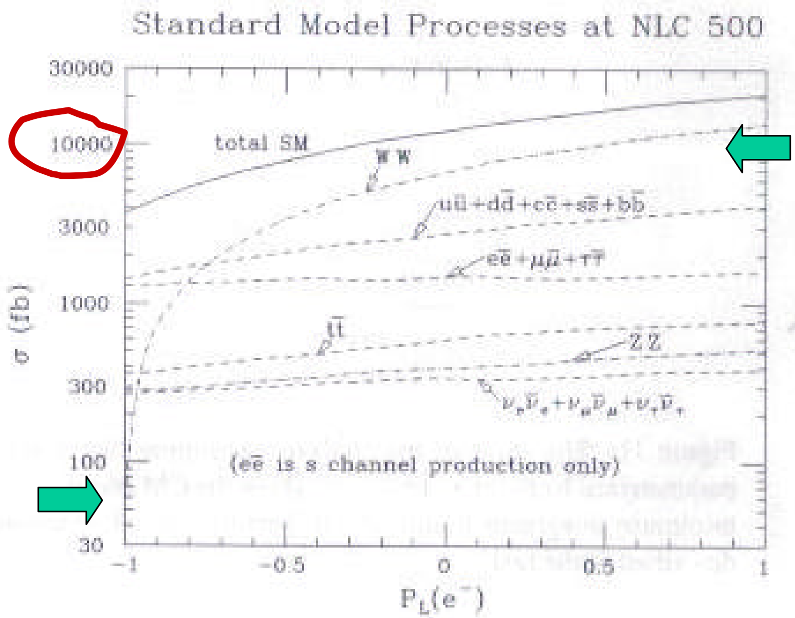


Figure 10: Cross sections of standard model processes as a function of electron polarization [3, 10].

Going to right handed electrons can heavily suppress WW background, which is most of cross section

Reminder: σ(ZH) is not very sensitive to polarization! It goes up about 15% for left polarization and down by 15% for right polarization from the un-polarized case.

However, W fusion→ σ(Hνν) is. RH Polarization turns off the W coupling!

This means that there is NO SIGNIFICANT conflict between between manipulating the polarization to do SUSY studies and accumulating statistics on a Higgs. Only possible problem would be if you want a lot of RH polarization running and you need the W fusion process for the Higgs to do some physics.

SUSY Scans

The SUSY mass spectrum can be quite complex. There can be several states (if lucky) within the machine's energy window. The left and righthanded sfermions do not have to have the same mass. There can be a lot of mass mixing between states.

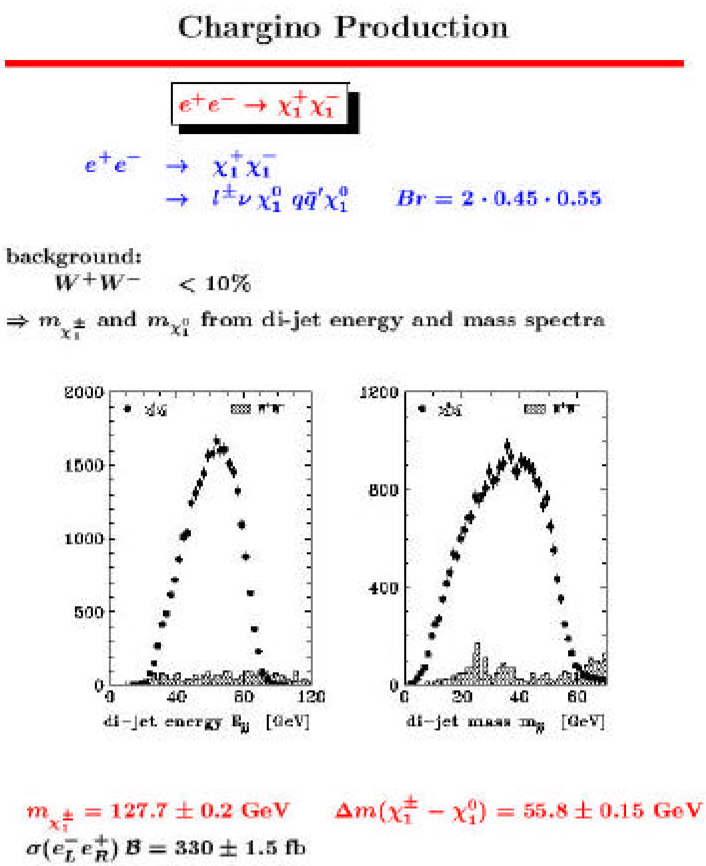
It seems desirable to vary the energy to see how the physics changes and to scan in the vicinity of thresholds to confirm quantum numbers, etc. SUSY is its own background!

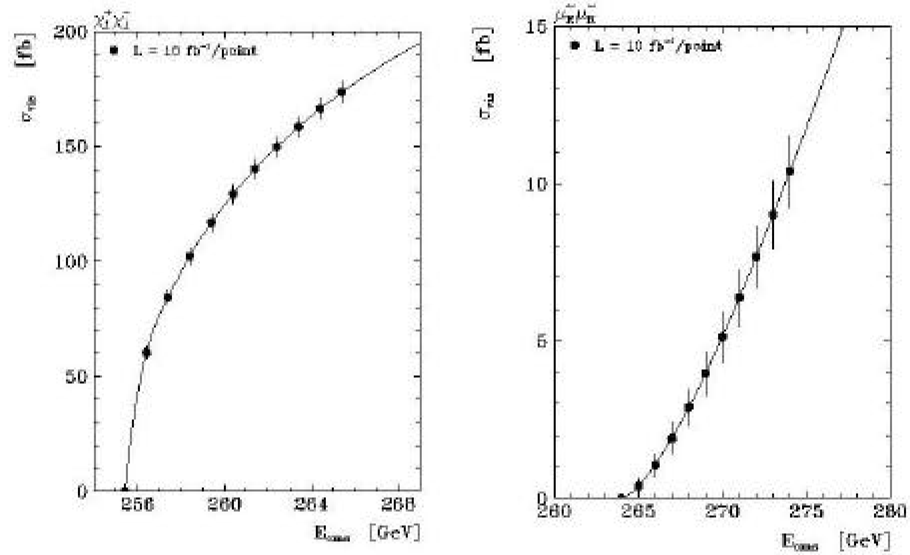
A SUSY program of investigations will involve varying energies as well as polarizations. We saw that the impact on the Higgs studies is not terribly great if you are running at HIGHER than optimal Higgs energy to do SUSY studies.

Of course, this would not necessarily be true if SUSY were at the light end of predictions or you found the heavier SUSY Higgs since they could be heavier than some of the sparticles. **This would be a good problem to have!**

SUSY Threshold Scan

10 energy points at 10 fb^{-1} each





From Martyn and Blair, LCWS, SUSY
Spectrum is similar to the first set above

Typical uncertainties on mass are 0.1 – 0.3 GeV/c^2 or a few parts per mil. From these, one can fit for SUSY breaking parameters in various models.

Note a strategy with only 4 points – above, below, 2 on the rise – has also been proposed.

Susy scans impact on other programs will depend on mass spectrum→ energy. Significant running with RH polarization (but you are running this way ½ of the time) or at low energy might hurt the Higgs or Top program or “new physics”.

Top Physics

The Top offers special opportunities for new physics because

•The large mass gives it strong couplings to many proposed new physics scenarios

•Couplings of Top quarks to EW gauge bosons are “largely untested” (and not all of this will be done at hadron colliders)

Scan (few 10 fb^{-1}) and sit <~100 fb^{-1} (theory limited?)

Topics near threshold (350 GeV) → σ~1000fb

1. Top Mass and Width – scan over 10 GeV around $2m_{t.}$
2. Top Width – height of 1S 1/Γ. The peak shape is also sensitive to $\Gamma_{t.}$
3. Top quark Yukawa coupling to the Higgs
4. Top quark threshold region in polarized e^+e^- collisions is sensitive to CP violation in top couplings and forward-backward asymmetry near threshold also gives info on Γ_t.

Sit. Anomalous couplings can use 500 fb^{-1} or more

Topics in continuum (500 GeV)→σ~600fb

1. ttH already discussed
2. Top mass may be measured well in continuum – work in progress
3. Anomalous couplings: analyze the energy and angular distribution of charged leptons and b-jets to see if they agree with SM predictions. There are CP violting electirc and magnetic dipole terms that could signify new physics

Physics Context at Turn-on or the “then-year” Physics Scenario

- We will have results that we do not have today from
  - **Tevatron: Nearly anything discovered at the Tevatron, Higgs, SUSY, or “other” would GUARANTEE that there was something very interesting to study at an LC**
  - **LHC: The LHC will almost certainly have a few years of running before an LC program will start. Much would depend on what was seen and how clear a picture emerged. The LHC experiments will have had a lot of time to study any new objects.**

If nothing is seen at the time the LC turns on, it would be first necessary to demonstrate in this new, cleaner environment that nothing was missed.

The "Then-year" Physics Scenario

Any LC program depends on

- What they learn at Tevatron and LHC– we should assume that their ability to learn things about Higgs, SUSY, or any new phenomena will improve as
  - running approaches and more people turn their attention to these issues
  - Results emerge to guide people's thinking and analyses
- Lessons learned from other physics (propagator/rare process) and theory
- Continuing studies of the kind now going on world-wide to understand how to exploit an LC

Possible Scenarios at LC turn-on

- 1 Higgs seen and evidence for SUSY – study Higgs, look for other Higgs', thoroughly explore SUSY
- >1 Higgs seen and evidence for SUSY
- 1 Higgs seen but nothing else – Study the Higgs to death, look for other Higg's and make sure SUSY not missed
- >1 Higgs seen and no SUSY evidence seen – study all Higgs thoroughly and make sure SUSY not missed
- 0 Higgs seen and no SUSY seen – make sure nothing is missed in cleaner environment and look for new phenomena

Don't forget that one must be also protect the opportunity to see something quite unexpected and be prepared to pursue anything new that shows up

Sample run plans for the first ~5 years

1 Higgs seen and evidence for SUSY

Risk taker

$100\ fb^{-1}$ max energy

$200\ fb^{-1}$ at Higgs optimum if step 1 indicates

$700\ fb^{-1}$ at max. energy or scan if SUSY scenario requires it.

Results will guide further running

1 Higgs seen but nothing else

$100\ fb^{-1}$ at max energy(quick check for new physics or missed SUSY)

$300\ fb^{-1}$ at Higgs optimum

$100\ fb^{-1}$ near top threshold

500 fb-^{1} at max energy (new physics, top anomalous couplings)

Consider Giga-Z running

0 Higgs seen and no SUSY seen and no new physics

$500\ fb^{-1}$ at 500 GeV(or highest energy) for new physics, WW scattering

$200\ fb^{-1}$ at tt threshold

Consider Giga-Z and WW threshold running

Conclusions –I

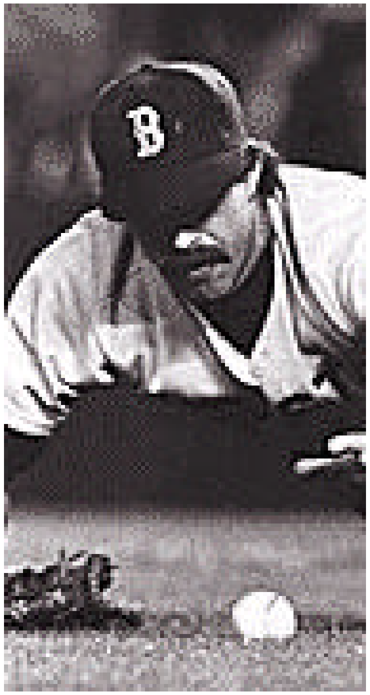
- Things you can do well: branching fractions and quantum numbers of Higgs, in depth SUSY studies for sparticles in this mass range….
- Things you can't do well with this luminosity: trilinear Higgs couplings, ttH
- Things you probably can't do at all with this luminosity: quadrilinear Higgs couplings…
- Things you can do with this luminosity but are much better at higher energy: trilinear coupling, ttH, and of course, you have better mass reach for heavier SUSY particles, heavier Higgs, and more reach for new phenomena
- **The potential for conflicts in operational modes that could drastically reduce the physics reach is low because**
  - Most physics is not sensitive to the precise CM energy. The production mechanisms do not involve s-channel resonances (**if there were new unforeseen ones, I somehow imagine we would consider this an opportunity rather than a problem!)**
  - the machine will normally alternate polarizations,
  - there are multiple ways of measuring most quantities,
  - once these phenomena begin to manifest themselves, some paths will be eliminated and others will be shown by the results to be the most productive to pursue.

Conclusions - II

- There is enough luminosity to realize an excellent program, especially if SUSY turns out to be correct since there the ability to manipulate polarization really pays off
- The various running modes are not so badly in conflict that major physics will have to be sacrificed or the program will have to be tuned in a way that could compromise ability to see unanticipated phenomena, provided
  - Polarization does not cost much luminosity
  - Changes in operating mode do not involve big inefficiencies (realignment, retuning) which sap integrated luminosity
- Further study will clarify which approaches are best for each measurement and search. Hopefully, people will keep operational realities in mind as they develop and advocate various approaches.
- Integrated Luminosity over the first N (5) years is critical – chose a technical approach that will achieve design luminosity quickly and maintain high efficiency. This should include an analysis of failure modes and maintenance issues
- Energy must be upgradeable in a straightforward manner to of order 800-1000 GeV and beyond at this site

Baseball slide 2

Red Sox Victory
6th game
1975 World Series



Red Sox Defeat
6th game
1986 World Series

Lesson: Make sure you have the best people in the game at the key moment

Credits and References

People who deserve credit for anything good in this talk but no blame for my mistakes:

Michael Peskin, Paul Grannis, David Burke, Chris Quigg, Steve Holmes
Carla of the Psychic Hotline
The "breakfast club": Chris Hill, Adam Para, Hugh Montgomery, Andy Beretvas, GP Yeh
All the Linedrive and Circle Line speakers

Some Useful References:

Proceedings of Snowmass 96
Perspectives on Supersymmetry, editor Gordon L. Kane
http://www.bostonredsox.com/
The Higgs Hunter's Guide, Gunion, Haber, Kane, and Dawson (still useful after all these years)
LCWS 2000
Tesla TDR
Physics at Run 2
http://store-yahoo.com/sportstation-steinersports/
The Case for a 500 GeV e+e- Linear Collider, American Linear Collider Working Group
http://www.whitesox.com/
many, many, many more